SASKATCHEWAN RESEARCH COUNCIL

A DEMONSTRATION PROJECT AT HUMBOLDT TO PROVIDE TERTIARY TREATMENT TO THE MUNICIPAL EFFLUENT USING AQUATIC PLANTS

by

G. Lakshman

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SYMBOLS AND UNITS

TPO_4, PO_4	Total Phosphates, mg/L All forms of phosphorus were converted into phosphates, measured and reported as phosphates. This includes soluble and insoluble components.
BOD	Biochemical Oxygen Demand, 5-day test, mg/L
TKN	Total Kjeldahl Nitrogen, includes both soluble and insoluble components, mg/L
m	Metre
ha	Hectare
d	Day
g, kg	Gram, kilogram
m^2	Square Metre
t	Retention Time, days
r	Correlation Coefficient
N	Sample Size
T	(Statistics) student 't', Total Growing season, days
W	Waterloss, $m^3/d/m^2$
P	Plant Density, stems/m^2
S, E	Seepage, Evapotranspiration, $m^3/d/m^2$
D1	Ditch 1, soil bottom
D2, D3	Ditch 2, Ditch 3 both gravel bottom.

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ABSTRACT

A growing concern for our environmental quality and the rising cost of providing adequate wastewater treatment have prompted a search for new, inexpensive and innovative treatment technologies. Conventional treatment methods are not applicable particularly in small communities because of their high capital, operational and maintenance costs. Simple aerobic or anaerobic stabilizing systems such as lagoons do not provide appreciable removal of nitrogen and phosphorus. Aquatic plants in natural or artificial wetlands remove nutrients from raw or partly treated sewage effectively and provide a viable and economically attractive alternative.

An artificial wetland stocked with cattail and bulrush was constructed at Humboldt, a town of 5,000 about 100 km east of Saskatoon. The system, consisting of two lagoons and three channels, occupying less than one hectare was initiated in late 1979. Primary and aerated sewages were used in a number of batch-fed treatment runs during 1979, 1980 and 1981.

Extensive data collected during these three years have shown that the artificial wetland performed effectively as a tertiary treatment system. This report, a review of the three-year program, highlights the results pertaining to retention time, nutrient loading, effect of gravel as a substrate, use of a bottom liner and the shape of the treatment site.

Algal density and diversity were generally different in ditches and lagoons, and the algal population declined rapidly with time after the beginning of the treatment runs. However, no correlations were observed

between algal growth and the treatment efficiency in each of these sites. Microbiological data related to fecal coliforms showed a definite decline with time during all runs.

SUMMARY

Aquatic plants such as cattail and bulrush when exposed to high levels of organic and nutrient loading not only survive and show high productivities but also remove large quantities of nutrients from the water. Systems exploiting this ecological adaptability can be effectively used to provide tertiary treatment to anaerobic or secondary effluents. This report reviews the results of a demonstration project at Humboldt, Saskatchewan, the first of its kind in Canada, where an artificial wetland was used to treat primary as well as aerated sewages, from August 1979 to November 1981.

The effluent from the town's sewage lagoons was pumped into the artificial wetlands, retained until the PO_4 and BOD levels were reduced by 80 to 90% and then discharged. The depth of sewage during treatment varied between 0.2 m and 0.5 m. Retention periods varied from 7 days to more than 100 days. Water samples were analysed for carbon, nitrogen, BOD and phosphorus. The main emphasis during the study was the renovation of sewage with respect to phosphorus and BOD. The nitrogen concentration in all treatment sites rapidly declined and hence did not cause concern.

Loss of water through seepage, transpiration and evaporation was influenced by plant density, ratio of perimeter to exposed area, and bottom lining (soil or gravel). Seepage through soil was 5 to 12 times more than the seepage through gravel bottom.

The loading rates varied from 13 to 380 Kg/ha for PO_4 from 4 to 889 Kg/ha for BOD, and from 26 to 277 Kg/ha for TKN. The corresponding concentrations varied from 2 to 71 mg/L for PO_4 from less than 10 to 144 mg/L for BOD and from 10 to 44 mg/L for TKN.

The rates of removal of nutrients increased non-linearly with the initial loading and retention time but tended to reach saturation values for retention times longer than three weeks.

The following table has been prepared from the data collected during the three-year period.

Retention Period (days)	PO_4 Removed (%)	BOD Removed (%)
7	36-75	60-86
14	48-82	66-90
21	61-92	58-92

Mean removal rates expressed as $g/d/m^2$ varied from 0.16 to 0.54 for PO_4, and from 0.39 to 1.91 for BOD, during the growing season.

For retention periods longer than a week, the unlined lagoon performed better. This should not preclude the use of a liner where it is required to prevent groundwater contamination. The use of gravel clearly increased the phosphorus removal by 60 to 90 percent. Lagoons were much more efficient than ditches for removing PO_4 and BOD for all retention periods, by a factor of 4.

A combination of ditches and lagoons is recommended to increase waterloss as well as nutrient removal.

Both PO_4 and BOD removal rates increased with the plant density.

Odour and mosquito problems were considerably less at the wetland site than at the town lagoon site.

OBJECTIVES AND CONCLUSIONS

The following conclusions are based on the field data and their analysis, and are given in relation to those objectives which are essential to the design and operation of similar wetland treatment systems.

Primary Objectives:

1. Determine the maximum rates of removal for phosphorus, nitrogen and BOD from untreated and partially treated sewage effluents by artificial wetlands treatment.

Nitrogen did not present any problems in so far as its removal was concerned. The wetland became low in nitrogen levels within a short retention time.

The rate of removal of phosphorus and BOD increased with the initial concentration, retention time and the plant density. (Tables 11-16, Fig. 2,3). But the rates of nutrient removal reached near saturation levels after 3 weeks and extending the retention time beyond this did not improve the treatment significantly.

Anaerobic as well as aerated effluents showed similar improvement in quality subject to the above mentioned parameters.

Using the three-year data, the variation in the rates of nutrient removal achieved during each treatment run, for all sites, is given in the following table.

Retention Time (days)	PO4 Removed (%)	BOD Removed (%)
7	36-75	60-86
14	48-82	66-90
21	61-92	58-92

The observed variation was essentially due to the variations in the initial nutrient loading, and plant density and was influenced by such parameters as the wetland type (lagoon, ditch) and gravel.

During a 150-day operation period for the wetland, approximately a maximum of 810 Kg/ha of PO_4 and a maximum of 2,865 Kg/ha of BOD could be removed.

An empirical relationship was obtained between PO_4 (x, in the equation) loading expressed in Kg, and the rate of PO_4 removal as Kg/d (Y, in the equation) in the form

$$Y = ax^b$$

where a and b were regression constants.
If Y is used as $Kg/d/m^2$ and X as Kg/m^2 this equation reduces to,

$$Y' = a' X'^{b'}$$

where Y' is the rate of PO_4 removal in $Kg/d/m^2$ and X' is the PO_4 loading per unit area as Kg/m^2.

The following table gives the constants a' and b' for lagoons and ditches.

WETLAND TYPE	a'	b'	Equation
Lined Lagoon	0.58	1.42	$Y' = (0.58) X'^{1.42}$
Unlined Lagoon	0.78	1.46	$Y' = (0.78) X'^{1.46}$
Ditches With Gravel Bottom	0.22	1.24	$Y' = (0.22) X'^{1.24}$
Ditches With Soil Bottom	0.52	1.33	$Y' = (0.52) X'^{1.33}$

Similarly, equations to compute the rate of removal of BOD as $Kg/d/m^2$ as a function of the BOD loading expressed as Kg/m^2 can be derived from

Table 16, and the corresponding constants are given in the following Table.

WETLAND TYPE	a'	b'	Equation
Lined Lagoon	0.13	1.11	$Y' = (0.13) X'^{1.11}$
Unlined Lagoon	0.10	0.98	$Y' = (0.10) X'^{0.98}$
Ditches With Gravel Bottom	0.32	1.28	$Y' = (0.32) X'^{1.28}$
Ditches With Soil Bottom	0.20	1.17	$Y' = (0.20) X'^{1.17}$

2. Determine the optimum retention time and nutrient loading rates required to treat a given volume and quality of sewage to a desired degree of treatment.

The rate of nutrient removal increased with the retention time but gradually reached saturation values. Retaining the sewage in wetlands longer than about 3 weeks did not improve wastewater quality and hence was uneconomical from the design point of view. It is, therefore, recommended a design retention time of less than three weeks, probably two weeks, should be considered. Statistically, the correlations obtained between the rate of nutrient removal and the retention time were not significant. The overriding influence of the loading rate on the removal rates did weaken the predictability of the effect of the retention time.

From the design point of view, the treatment area should relate to a reasonable retention time less than 3 weeks so that it can provide the required nutrient reduction. Increasing the depth of operation so as to decrease the required treatment area can only be done within narrow limits. An optimum depth is between 0.3 and 0.5 m, and greater depths will only result in lower nutrient removal efficiency and may adversely affect the survival rates of cattail. However, if the influent has already undergone secondary treatment before being pumped into the wetland, then it may be possible to use slightly greater water depths. This conclusion is substantiated by studies related to natural wetlands in the U.S.

3. Determine if the technique reduces nuisance odours, faecal coliforms and enteric pathogens.

It was obvious even when anaerobic effluent from the town's primary lagoon was pumped into the wetlands, the odour did not persist once the pumping was completed. The rapid aeration that the effluent received while being pumped through the irrigation pipes apparently increased its oxygen content. Subjective evaluation of the odours from the wetlands as well as from the town's primary lagoon confirmed that odours were definitely reduced in the wetlands.

There was a significant reduction in total coliforms and faecal coliforms. About 97% of the measured values for coliforms were less than the limit imposed for secondary-treated effluents. About 61 met the criteria for potable supplies before treatment and about 42 were less than the limits for surface waters designated for contact recreation.

counts were less than 1,000 and 200 per 100 mL, respectively.

The bacteriological monitoring, although produced some useful indications of the effect of wetland treatment on the total coliforms and faecal coliforms, was inadequate to provide definite predictable trends in the bacterial populations.

However, significant reductions observed in the faecal coliform populations indicate that wetlands can prove effective in improving bacteriological quality of sewage.

4. Evaluate the overall performance of the system for large scale, rapid treatment and discharge of effluents and to determine the necessary design parameters for the system such as loading rates, depth, operational mode, harvesting techniques, and overall costs.

The study showed that cattail and bulrush grown in lagoons or in ditches, in gravel substrates or in soil, and lined or unlined areas could be effectively used to provide nutrient removals from raw as well as aerated sewage. However, the degree of purification achieved during a given retention time depended on the initial loading, depth, plant density and the site parameters such as the substrate, lining and the shape of the wetland.

Liners serve the essential purpose of eliminating groundwater contamination from sewage storage or treatment ponds. Its use did not enhance the removal of nutrients and, therefore, should be considered strictly from the groundwater pollution point of view.

Lagoons are preferred to ditches as they removed roughly 4 times more nutrients from the same growing area than the ditches. In view of the availability of natural ditches in almost all sites, a combination of ditches and lagoons should be considered as an alternative.

Gravel substrate, although expensive as an initial capital cost, should be included as its use was found to increase the phosphorus removal by 60 to 90 percent. However, a reduction in seepage should be anticipated due to the use of gravel and this would probably affect the total treatment area required in some cases.

The optimum depth of operation should be designed to be less than 0.5 m and preferably between 0.3 and 0.5 m.

The rate of nutrient removal (phosphorus and BOD) was highly correlated with the plant density. The increase in plant density varied from less than 10% to more than 400% from one year to the next. The smaller the initial plant density, the greater was the increase during a year. The initial plant density starting from about $20/m^2$ and higher can be used depending upon the urgency of the sewage treatment requirement and the availability of funds to cover the costs. In view of the high productivity of aquatic plants and the efficient vegetative propagation the nutrient removal efficiency of artificial wetlands will show an annual increase. Owing to the short duration of the study at Humboldt, it is not possible to extrapolate the results to indicate if and when the plant growth would reach a saturation stage.

A simple and effective method of harvesting the above-ground portion of plants after freeze-up was to raise the water level to about 60 cm,

let it freeze and cut plants using a sickle mower. This involved approximately 96 hours to harvest from the two lagoons and the three ditches. The cost was less than $475.00. It is essential to include the cost of harvesting and material removal in the annual operating costs.

A procedure to design a wetland system is given at the end of this section with cost figures from the Humboldt set-up and a conventional advanced treatment system.

Secondary Objectives

1. Evaluate the quality and quantity of re-useable water available after treatment.

The concentrations of BOD, nitrogen and phosphorus of anaerobic as well as aerated sewage after wetland treatment were reduced to levels acceptable for discharge into surface waters. The bacterial contamination in terms of total coliform counts and faecal coliforms was significantly reduced.

The ditches lost roughly three times more water than the unlined lagoon. Approximately, between 75 and 30% of wastewater could be recovered for re-use from lagoons and ditches, respectively when retained for less than 2 weeks.

2. Determine the cost of harvesting the biomass and maintaining the treatment system.

It is essential to harvest at least once but preferably more frequently if possible. At Humboldt, using a sickle mower and operating

after freeze-up it took less than 100 hours to cut the plants about 6 cm above the ice and rake them for bagging. The total cost was approximately $475.00.

During the 1979 winter and the spring of 1980, there was some loss of plants either due to lack of snow cover to protect the roots from freezing or due to the fact that they were transplanted from freshwater wetlands. The loss was made up by stocking the bare patches in the lined and unlined lagoons. But this does not appear to be a serious problem. Snow fences were installed to conserve snow cover in lagoons but this effort may not be necessary in most circumstances.

The need for harvesting the above ground parts of the plants arises because, 1) at the end of the growing season the dead leaves would, if not harvested, begin to decay and the nutrients would be leached back into the wetland system, 2) the dead leaves would begin to clog the system, and 3) harvesting the plants provides a method for exporting the nutrients accummulated in the leaf tissues out of the site.

The cost of harvesting, either manually or mechanically, should be included in the operating costs of the treatment system. And at least one harvest per year after freeze-up should be scheduled.

3. Evaluate the suitability of the harvested biomass as an animal feed and determine the economics.

Plant samples taken from lagoons and ditches were analysed for their feed value and the results are presented in the following tables. Samples from leaves and rhizomes were analysed separately. The samples had

high fiber content because of late harvesting. Typical ranges of values for ammonia-treated straw for crude protein and digestible organic matter (DOM) are 10-15% and 35-45%, respectively.

The economics of the use of the harvested biomass as livestock feed can only be determined after feed-trials with ruminants. It is hoped that this aspect of the biomass utilization in a wetland treatment scheme will be followed up in the coming years. No work was done on improving the digestibility by silaging the biomass.

Table 1
Feed Analysis of Cattail Leaves
(% Dry Matter Basis)

Location	Date	Crude Protein	Fat	Fiber	Phosphorus	Ash	DOM	Calcium
Lined	27/10/79	18.91	2.88	19.88	0.50	12.97	51.92	-
	26/09/80	15.33	3.11	24.99	0.28	6.37	45.98	0.87
	19/11/80	5.82	2.16	34.97	0.13	6.32	25.15	1.13
Unlined	27/10/79	19.57	2.87	18.62	0.43	12.37	51.74	-
	26/09/80	14.70	3.21	26.86	0.22	5.96	46.41	0.82
	19/11/80	7.09	2.03	33.84	0.12	8.77	31.23	0.74
D_1	27/10/79	15.58	-	-	-	-	-	-
	26/09.80	12.84	2.91	29.44	0.21	6.73	40.92	0.78
D_2	27/10/79	17.63	2.55	19.43	0.28	13.99	47.81	-
	26/09/80	15.33	2.99	26.11	0.22	5.75	43.30	1.00
	19/11/80	6.76	2.98	35.30	0.14	4.97	23.00	1.22
D_3	27/10/79	18.49	1.92	19.50	0.29	17.71	48.30	-
	26/09/80	14.13	3.10	27.44	0.22	5.15	42.10	0.93
Mean		14.01	2.72	26.27	0.25	8.92	41.49	0.94
S. Deviation		4.7	0.5	6.5	0.1	4.2	9.8	0.2

Table 2
Feed Analysis of Cattail Rhizomes
(% Dry Matter Basis)

Location	Date	Crude Protein	Fat	Fiber	Phosphorus	Ash	DOM	Calcium
Lined	10/79	6.66	1.03	22.22	0.25	-	38.27	-
Unlined	10/79	7.32	0.95	21.52	0.32	-	44.94	-
D_1	1/11/79	8.08	0.92	17.11	-	-	-	-
D_2	1/11/79	9.26	1.61	19.25	0.22	-	40.84	-
D_3	1/11/79	-	1.07	27.73	-	-	-	-
Mean		7.83	1.12	21.57	0.26	-	41.35	-
S. Deviation		1.12	0.28	3.99	0.05	-	3.36	-

Table 3
Feed Analysis of Bulrush Leaves
(% Dry Matter Basis)

Location	Date	Crude Protein	Fat	Fiber	Phosphorus	Ash	DOM	Calcium
Lined	27/10/79	13.85	2.50	25.86	0.25	10.39	52.82	-
	26/09/80	13.59	2.94	28.61	0.33	10.08	47.43	0.94
	19/11/80	5.86	1.72	32.60	0.13	8.95	31.55	0.87
Unlined	27/10/79	19.05	2.38	20.66	0.34	13.27	57.94	-
	26/09/80	15.15	2.52	27.38	0.23	10.03	49.96	0.81
	19/11/80	4.96	2.29	35.63	0.10	4.49	20.03	0.98
D_1	27/10/79	15.49	2.22	26.40	0.19	9.91	57.94	-
	26/09/80	12.62	2.20	27.90	0.19	12.21	51.03	0.91
D_2	27/10/79	15.26	2.06	25.76	0.17	10.90	54.59	
	26/09/80	13.80	1.68	28.10	0.23	10.18	48.64	
D_3	27/10/79	17.00	2.84	23.29	0.18	10.71	56.39	
	26/09/80	13.06	2.25	26.10	0.24	9.22	41.60	
	19/11/80	7.68	2.07	34.61	0.15	7.76	27.30	
Mean		12.88	2.28	27.92	0.21	9.85	45.94	0.90
S. Deviation		4.2	0.4	4.2	0.1	2.1	12.3	0.1

Table 4

Feed Analysis of Bulrush Rhizomes

(% Dry Matter Basis)

Location	Date	Crude Protein	Fat	Fiber	Phosphorus	Ash	DOM	Calcium
Lined	27/10/79	10.30	0.59	20.90	0.26	-	48.84	-
Unlined	27/10/79	7.69	-	-	-	-	-	-
D_1	1/11/79	10.68	0.88	22.80	0.27	-	49.41	-
D_2	1/11/79	9.31	0.93	21.18	0.17	-	46.56	-
D_3	1/11/79	8.57	0.59	20.56	0.20	-	47.97	-
Mean		9.31	0.75	21.36	0.23	-	48.20	-
S. Deviation		1.23	0.18	0.99	0.05	-	1.24	-

4. Develop a comparison with the conventional secondary and tertiary treatment systems in terms of cost and treatment efficiency.

The following are the approximate costs incurred at the Humboldt site.

1.	Earthwork	$ 11,000.00
2.	Liner	11,663.00
3.	Gravel. Material	8,551.00
	Labour	1,265.00
4.	8 Culverts, 5 gates	2,000.00
5.	Pump and pipes with adjustable gates	4,790.00
6.	Pumphouse, electrical	3,170.00
7.	Transplanting, labour	14,078.00
8.	Fence	1,240.00
9.	Supervision, SRC staff	16,092.00
	Total	$73,849.00

Simplicity of construction and operation of the artificial wetland treatment system would make it more reasonably priced than the conventional tertiary treatment plants. A simplified comparison of the artificial wetland concept with several alternatives proposed for the town of Fort Qu'Appelle is given in the following table. The capital costs for the conventional alternatives are obtained from the 'Review of Advanced Wastewater Treatment Options' conducted by the Underwood McLellan Ltd. for the town of Fort Qu'Appelle in 1979. The numbers refer to the cost per cubic metre of sewage treated. The costs for the artificial wetland system does

not include the liner and the supervision of SRC staff. Being a comparison of the treatment systems the table does not include the cost of any winter storage.

Table 5

An Approximate Comparison of Treatment Costs

Treatment Alternative	Costs ($/m^3 of sewage treated) Capital	Annual Operating Costs
1. HUMBOLDT		
A. Artificial Wetland (for 200 m^3 flow per day)	0.59	0.04
2. FORT QU'APPELLE (1,364 m^3 flow per day)		
A. Chemical Treatment	0.74	0.14 - 0.25
B. Tertiary Treatment	0.97	0.19 - 0.34
C. Advanced Bio-treatment	1.81	0.22 - 0.32
D. Irrigation	2.32	0.21 - 0.26

A PROCEDURE TO ESTIMATE DESIGN PARAMETERS

The wetland treatment lagoon is so designed that the 12-month sewage production is treated and discharged during the growing season.

The design parameters to be estimated for a given application are,

A, area of the treatment site, hectares

t, mean retention time, days.

They are estimated for the following site-specific conditions.

Q, the total annual sewage flow, m^3

T, total duration of the growing season, days

P_R, percentage PO_4 reduction that the wetland treatment system is expected to provide, (this is computed from the PO_4 concentration in the untreated sewage and the concentration required before discharge). As there is very little choice in the selection of the operating depth, it is assumed here to be 0.5 m. The following example does not take into consideration the water-loss due to evaporation, seepage and transpiration nor does it involve any specific plant density. The equations, which are used here represent the plant densities observed at the Humboldt set-up, from 1979 to 1981.

1. Compute Mean Retention Time:

Using the equation for the rate of PO_4 removal as a function of the initial loading rate, for unlined lagoon given in the discussion under objective 1, we have

$$Y' = (0.78)\, X'^{1.46} \qquad (1)$$

where Y' is PO_4 removed, $Kg/d/m^2$

X' is PO_4 loading, Kg/m^2

And, $P_R = \frac{(Y't)\ 100}{P_i}$ (2)

= percentage PO_4 loading removed in t days,

where P_i is the initial loading, Kg/m^2.

And, P_i is given by $P_i = (C_i d)\ 10^{-3}$

where C_i is the initial PO_4 concentration, in mg/L

d is the depth, m

Combining equations (1) and (2), we get

$$P_R = \frac{(0.78)\ (X')^{1.46}\ t.\ 100}{P_i}$$

As $X' = P_i$ = initial loading

$$P_R = (78)\ t\ P_i^{0.46}$$

$$= (78t)\ [C_i d\ 10^{-3}]^{0.46}$$

Solving for t, the mean retention time, we get

$$t = \frac{P_R\ [C_i d\ 10^{-3}]^{-0.46}}{78}$$

for d = 0.5 m, $t = (0.42)\ P_R C_i^{-0.46}$

The following gives retention times for various P_R and C_i combinations.

P_R (%)	C_i (mg/L)			
	5.0	10.0	15.0	20.0
50	10	7	6	5
70	14	10	8	7
80	16	12	10	8
90	18	13	11	9

2. Compute Wetland Treatment Area

If Q_o is the sewage flow per day, m^3/d

A_t is the treatment area required, hectare

d is taken to be 0.5 m.

then, $Q = (365)\ Q_o = (T/_t)\ (A_t\ d\ 10^4)$

Solving for A_t, we get

$$A_t = \frac{(365)\ Q_o\ (t/_T)}{(d\ 10^4)}$$

$$= (0.073)\ Q_o\ (t/_T)$$

Taking T = 150 days,

$$A_t = (4.9 \times 10^{-4})\ Q_o\ t$$

The following table gives A_t in hectares for various values of Q_o and t.

	t (days)			
Q_o m^3/d	5	7	10	15
45	0.11	0.15	0.22	0.33
225	0.55	0.77	1.10	1.65
675	0.65	2.32	3.31	4.96
900	2.21	3.11	4.41	6.62
2,250	5.51	7.72	11.03	16.54

DEMONSTRATION SITE

Conventional methods for storing and stabilizing sewage continue to use open and deep lagoons whereas artificial and natural channels or raceways may prove to be less expensive in this respect although they do not provide comparable storage. For this reason, the demonstration set up at Humboldt consists of two lagoons and three ditches so as to determine the relative economic merits of employing a lagoon or a ditch for sewage treatment. The lagoons are 90 m long, 45 m wide, and about 1 m deep. One of the lagoons is lined with a 15 mil PVC liner so that its performance without a soil bottom in terms of waterloss, nutrient removal and plant growth can be compared with that of the unlined lagoon. All sites were stocked with bulrush and cattail in gravel substrates except ditch 1 where the plants were grown in soil. This set up provides a comparison between the lined and unlined lagoons, between the ditches and the unlined lagoon, and between the ditches with gravel and the ditch without gravel.

The density of plants in the lagoons was improved by additional plantings in 1980 and 1981. Plant densities were not measured in 1979 but were obtained in 1980 and 1981. The physical set-up of the treatment sites is summarized in Table 1. The plant densities in the treatment sites measured in 1980 and 1981 are given in Table 2.

Although additional plants were transplanted to fill in the bare patches in the lagoons, there was an impressive growth of plants in all sites in terms of flowering, growth height, early spring growth and late onset of senescence in fall. Sewage for treatment in the artificial wetland was obtained either from the town's primary (anaerobic) cell or from

Table 6

PHYSICAL CHARACTERISTICS OF THE TREATMENT SITES

SITE	AREA (m^2)	DEPTH (m)	SUBSTRATE	PLANTS	REMARKS
LINED LAGOON	4050	1.0	Gravel	Cattail Bulrush	Lined with PVC Liner
UNLINED LAGOON	4050	1.0	Gravel	Cattail Bulrush	-
DITCH 1	180	1.0	Soil	Cattail Bulrush	-
DITCH 2	180	1.0	Gravel	Cattail Bulrush	-
DITCH 3	180	1.0	Gravel	Cattail Bulrush	-

Table 7

PLANT DENSITIES IN THE TREATMENT SITES
(Includes both Cattail and Bulrush)

Treatment Site	Plant Density (STEMS/m^2)		
	1980	1981	% increase
LINED LAGOON	17.8	94.1	428
UNLINED LAGOON	21.2	59.9	183
DITCH 1	142.2	216.5	52
DITCH 2	74.3	126.7	71
DITCH 3	92.1	94.7	3 %

the storage lagoons. Humboldt's lagoon system includes one primary cell, one continuously aerated lagoon and three storage lagoons occupying approximately 23 hectares. The discharged sewage from these lagoons flows through a well-defined ditch to the Stoney Lake (Humboldt Lake). The artificial wetlands occupying less than a hectare (8640 m^2) are situated adjacently north of the town lagoons. The discharged effluent from the treatment site is conveyed to a large natural swamp west of the area by a roadside ditch.

A sketch of the layout of the demonstration site is shown in Figure 1.

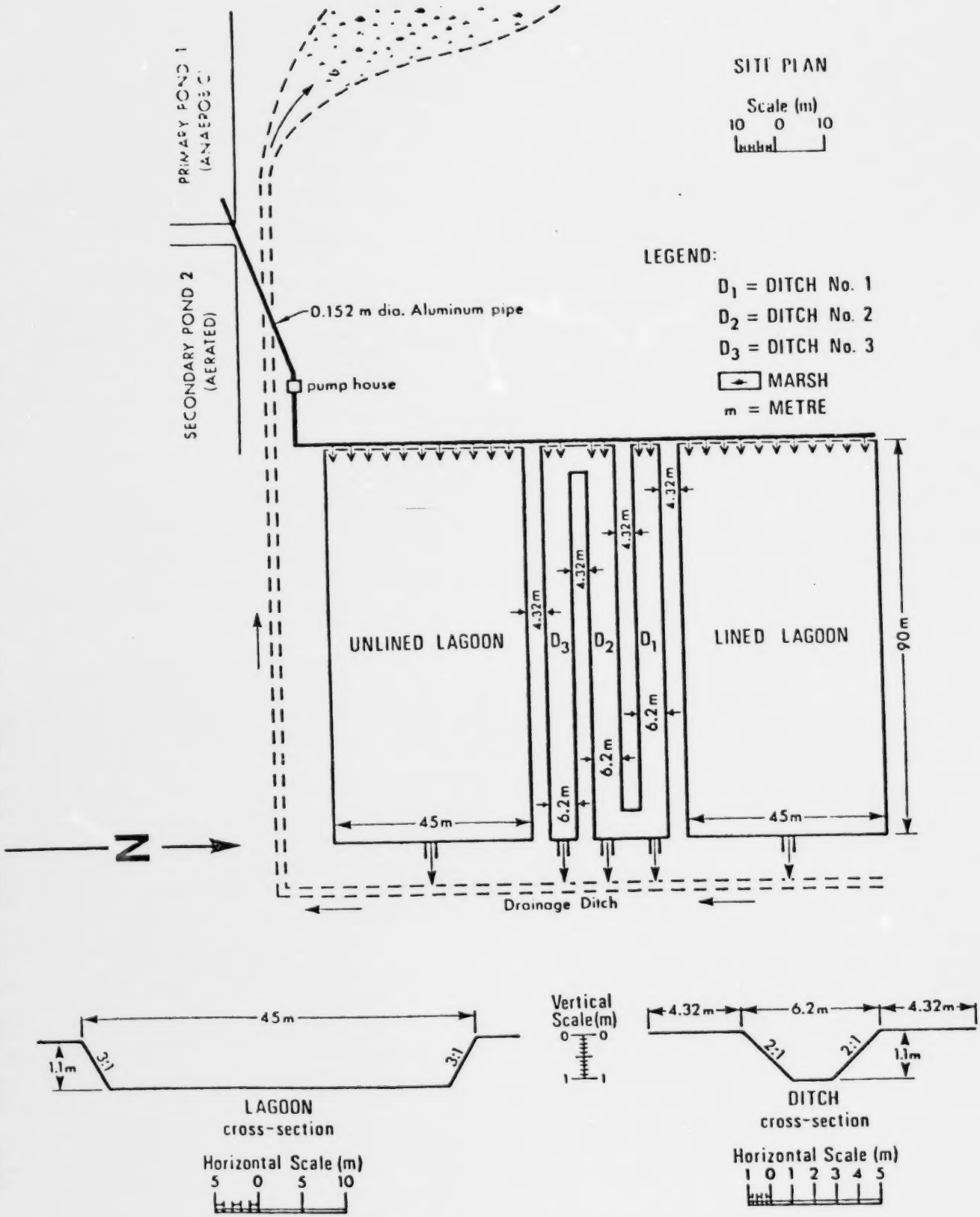

Figure 1 Layout of the Treatment Lagoons and Ditches at Humboldt

TREATMENT SCHEDULES

Sewage for treatment was obtained from the anaerobic primary cell as well as from the storage lagoon during 1980 and 1981, whereas in 1979 only the primary sewage was used. Table 3 shows effluent sources for various treatment runs. Table 4 gives the PO_4 and BOD levels in the samples taken from the various town lagoons. The BOD levels are rather low indicative of weak sewage except in the case of two samples taken from the primary cell.

Sewage from the town lagoons was pumped into the artificial wetland sites and retained until the phosphorus level was reduced by about 80 to 90 percent of the initial value. It was then discharged and a new batch was pumped in. In many instances, the sewage was retained much longer than this period to determine if there were any releases of the absorbed nutrients back into the system. Table 5 summarizes the retention times for all runs during the three years of operation.

Quality of the influent was highly variable and the sewage was found to be low in BOD for most of the runs. High dilution waters in the sewers or the vigorous aeration during the pumping process might have contributed to this situation.

Table 8

SOURCES OF SEWAGE FOR TREATMENT RUNS

	RUN	LINED L.	UNLINED L.	D1	D2	D3
1979	All	Anaerobic Primary Effluent Used For All Runs				
1980	1	Primary	Primary	Primary	Primary	Primary
	2	Primary	Primary	Primary	Primary	Primary
	3	Secondary	Secondary	Primary	Primary	Secondary
	4			Secondary	Secondary	Secondary
	5		—	Secondary	Secondary	Secondary
1981	1	Primary	Primary	Primary	Primary	Primary
	2	Primary	Primary	Primary	Primary	Primary
	3	Secondary	Secondary	Primary	Secondary	Secondary
	4			Secondary	Secondary	Secondary
	5			Secondary		
	6			Secondary		

Primary Effluent was obtained from the anaerobic cell
Secondary Effluent was obtained from the storage lagoon (H_3) containing sewage after continuous aeration.

Table 9

PHOSPHORUS AND BOD LEVELS IN SAMPLES FROM TOWN LAGOONS

Sampling Date	Lagoons H_1		H_2		H_3		H_4		H_5	
	PO_4	BOD	PO_4	BOD	PO_4	BOD	PO_4	BOD	PO_4	BOD
	----------		----------		-----mg/L-----		----------		----------	
1981										
May 21	21.0	-	22.0	-	21.0	-	15.0	-	8.3	-
June 10	82.0	95.0	16.0	18.0	14.0	6.0	14.0	6.0	6.0	6.0
June 29	15.0	-	9.6	-	12.0	-	22.0	-	9.2	-
July 22	11.0	48.0	12.0	40.0	2.5	4.0	4.8	4.0	3.1	2.0
Aug. 12	12.0	138.0	8.7	20.0	11.0	7.0	11.0	13.0	5.4	10.0
Sept. 9	19.0	149.0	9.8	12.0	8.6	5.0	1.9	4.0	5.9	2.0
Sept. 23	1.8	76.0	2.8	16.0	2.4	4.0	1.8	<1.0	2.3	<1.0
1980										
May 7	16.0	84.0	16.0	22.0	12.0	12.0	11.0	9.0	3.2	16.0
May 22	13.0	98.0	-	-	-	-	-	-	-	-
May 27	13.0	85.0	-	-	-	-	-	-	-	-
July 10	14.0	90.0	-	-	-	-	-	-	-	-
Aug. 26	-	-	6.9	10.0	-	-	-	-	-	-
Sept. 11	-	-	7.8	19.0	-	-	-	-	-	-

H_1 Primary anaerobic lagoon
H_2 Continuously aerated lagoon
H_3, H_4, H_5 Storage lagoons.

Table 10

RETENTION TIMES USED IN VARIOUS RUNS

(days)

SITE	YEAR		
	1979	1980	1981
LINED LAGOON	25,30	41,46,69	26,33,102
UNLINED LAGOON	25,30	41,70,42	47,32,102
DITCH 1	25,30	32,28,52,11,42	40.15,15,11,7,70
DITCH 2	25,30	32,31,49,11,42	47,28,32,70
DITCH 3	25,30	63,32,16,11,42	47,28,32,70

WATERLOSS

Unlined treatment sites lose water through evaporation, seepage and transpiration. These water losses reduce the storage or treatment areas required to treat a given volume of effluent and should be considered when designing wetland lagoons or ditches. Seepage loss increases with the depth of water and the dimensions of the treatment site such as the perimeter and the bottom area. But evaporation and transpiration losses vary during the growing season reaching a maximum sometime during July or August. Transpiration rates depend upon the plant density and the plant species. Like evaporation the rates depend upon the meteorological parameters such as air temperature, humidity, wind speed and insolation. Evaporation losses decrease as the plant cover increases due to the diminishing exposed area and increasing shelter factor. Table 6, presents waterloss data measured from all sites. The data for 1979 represent the losses during the short period of operation from August 29 to October 24. It is clear that the shape of the wetland and the presence of gravel substrate influence the rates of waterloss. The ditches, because of their higher perimeter to area ratio than the lagoons, lost almost four times more water through seepage than the unlined lagoon. The perimeter to area ratios are 1.02 and 0.07 for ditches and lagoons respectively. Infiltration losses in the ditches with gravel were less than the losses in the ditch with soil. Using the percentage fractions of evaportranspiration and seepage from 1981 data, corresponding components for 1979 and 1980 were obtained. These are given in Table 7. A comparison of waterloss rates to indicate the influences due to the shape factor and the nature of substrates is given in Table 8. Seepage losses from a soil

laden ditch can be as much as 12 times the seepage loss from a lagoon with a gravel bottom.

Transpiration loss from the plants increased with the plant density in all sites according to the following regression equation.

$$W = - 0.0072 + (0.00017)\ \rho$$

Where W is the observed waterloss, $m^3/d/m^2$ and ρ is the plant density, stems/m^2.

Table 11

RATES OF WATERLOSS FROM TREATMENT SITES

(mean values, $m^3/d/m^2$)

SITE	1979	1980	1981
LINED LAGOON	1.4×10^{-3}	2.9×10^{-3}	3.4×10^{-3}
UNLINED LAGOON	2.6×10^{-3}	3.3×10^{-3}	4.3×10^{-3}
DITCH 1	8.9×10^{-3}	19.6×10^{-3}	33.9×10^{-3}
DITCH 2	8.2×10^{-3}	10.8×10^{-3}	11.4×10^{-3}
DITCH 3	6.8×10^{-3}	10.7×10^{-3}	9.7×10^{-3}

Except for the 1979 data all other data have been corrected for rainfall.

Table 12

WATERLOSSES DUE TO SEEPAGE (S) AND EVAPOTRANSPIRATION (E)

($m^3/d/m^2$)

	1979		1980		1981	
	S	E	S	E	S	E
L. LAGOON	-	1.4×10^{-3}	-	2.9×10^{-3}	-	3.4×10^{-3}
U. LAGOON	1.3×10^{-3}	1.3×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	2.1×10^{-3}	2.2×10^{-3}
DITCH 1	6.9×10^{-3}	2.1×10^{-3}	5.1×10^{-3}	4.5×10^{-3}	26.0×10^{-3}	7.8×10^{-3}
DITCH 2	4.9×10^{-3}	3.2×10^{-3}	6.5×10^{-3}	4.3×10^{-3}	6.8×10^{-3}	4.6×10^{-3}
DITCH 3	4.4×10^{-3}	2.4×10^{-3}	6.9×10^{-3}	3.8×10^{-3}	6.3×10^{-3}	3.4×10^{-3}

These values have been computed using percentage fractions for E and S obtained from 1981 data.

Table 13

COMPARISON OF WATERLOSS RATES

	1979	1980	1981
UNLINED LAGOON / LINED LAGOON	1.85	1.14	1.27
MEAN OF D_2, D_3 / UNLINED LAGOON	2.86 (3.58)	3.23 (4.19)	2.44 (3.12)
DITCH 1 / MEAN OF D_2, D_3	1.19 (1.48)	1.82 (2.25)	3.21 (3.97)
DITCH 1 / UNLINED LAGOON	3.40 (5.30)	5.88 (9.43)	7.83 (12.39)

The numbers within perenthesis are ratios of seepage losses.

LOADING RATE, RETENTION TIME AND NUTRIENT REDUCTION

During the three years of operation both anaerobic and aerated sewage with variable organic and nutrient loading were used in the treatment runs. The loading rates for lagoons and ditches, therefore, varied considerably as shown in Table 9. The application rate varied from 13 to 380 kg/ha for PO_4, from 4 to 889 kg/ha for BOD and from 26 to 277 kg/ha for TKN. The same information in terms of concentration ranges are given in Table 10. No odour problem was encountered when the application rates with anaerobic effluent reached high values. Slug loading rates of up to 889 kg/ha of BOD with depths ranging from 0.2 to 0.5 m were safely used. From this experience and results from other studies it appears safe to use an application rate of up to 1,500 kg/ha/day for BOD if precautions are taken not to cause stagnation at the point of inflow.

Generally, significant reductions were achieved in phosphorus, BOD and Nitrogen. The rates of removal depended on the initial loading, retention time, depth of operation and the stage of plant growth. Although the nutrient reduction during a given retention time increased with the initial loading at the beginning of the period, the rate of nutrient removal increased less predictably as the retention time was extended. At high application rates, of the order of 100 kg/ha or more, most of the nutrients was removed in the first week of retention and very little improvement was achieved in the following weeks. On the other hand, low application rates such as typical of aerated sewage application from the storage lagoon, resulted in a gradual removal of nutrients over a long period. The dependence of the degree of removal achieved on the application rate and the period of retention showed, in general, poor to good

Table 14

RANGE OF NUTRIENT LOADINGS (kg/ha)

Location	PO_4	BODs	TKN
		1979	
LINED	22.7 - 59.0	70.6 - 325.7	38.8 - 146.4
D_1	27.8 - 58.9	277.8 - 350.0	44.4 - 144.4
D_2	12.S - 58.9	118.9 - 313.3	26.1 - 131.7
D_3	18.9 - 55.6	170.6 - 281.1	38.3 - 157.8
UNLINED	24.9 - 25.4	78.3 - 103.0	29.9 - 57.8
		1980	
LINED	30.4 - 59.5	45.7 - 285.9	59.8 - 170.6
D_1	29.4 - 99.4	60.6 - 822.2	91.7 - 276.7
D_2	12.8 - 61.1	16.7 - 421.1	68.3 - 141.1
D_3	17.2 - 59.4	28.3 - 410.6	58.3 - 140.6
UNLINED	22.5 - 44.7	19.6 - 128.6	67.9 - 162.2
		1981	
LINED	67.9 - 167.4	18.9 - 57.0	50.9 - 93.8
D_1	55.6 - 358.3	35.0 - 888.9	92.8 - 235.6
D_2	53.9 - 295.0	4.44 - 635.0	49.4 - 173.9
D_3	51.7 - 380.0	4.44 - 425.6	63.9 - 150.0
UNLINED	24.9 - 54.1	16.9 - 42.2	38.3 - 91.1

Table 15

VARIABILITY IN THE INITIAL CONCENTRATIONS OF PO_4, BOD AND TKN

(mg/L)

Site	PO_4			BOD			TKN		
	'79	'80	'81	'79	'80	'81	'79	'80	'81
LINED LAGOON	2-13	8-15	20-50	2*-60	12-72	10-41	15-31	15-33	15-28
UNLINED LAGOON	6-8	7-13	13-16	32-35	6*-60	5*-34	13-18	33-44	14-27
D1	11-13	4-13	11-56	77-115	8*-96	7*-144	18-32	12-32	16-32
D2	3-13	3-13	12-61	45-68	3*-86	1*-117	10-29	13-31	11-32
D3	5-10	3-12	10-71	48-50	5*-83	1*-80	11-28	10-31	14-28

* Low levels, measured values not reliable.

correlations. In practice it is important to reduce retention times as much as possible because longer retention times would mean fewer treatment runs and hence less volume of sewage treated during the growing season. Tables 11 and 12 show that phosphorus removal was highly correlated with the initial loading in most cases but the correlations obtained for BOD were generally bad except in a few cases. Similar responses were obtained for correlations with respect to retention time as shown in Tables 13 and 14. Low BOD levels, often less than 30 mg/L, in the influent were rapidly reduced to less than 10 mg/L and at these very low levels neither the initial loading nor the retention time had any influence. The rate of PO_4 and BOD removal, in terms of kg/d were highly dependent on the quantity of the nutrient remaining at the beginning of each sampling period. Tables 15 and 16 show the statistical data for all years.

The reduction in PO_4 and BOD levels can be estimated for any retention period using an equation of the type:

$$Y = 100\ (1 - ae^{-bt})$$

Where Y is the percentage reduction, t is the retention time in days, and a and b are regression constants. Alternately the percentage reduction achieved during a given retention time depends upon the initial loading in the form:

$$y = a_1 x^{b_1}$$

Where Y is the percentage reduction, x is the initial loading in kg/ha, a_1 and b_1 are regression constants.

Table 16

PO_4 REDUCTION AS A FUNCTION OF INITIAL LOADING

(Y = % Reduction: x = Initial Loading, Kg/ha)

Year		Retention time (days) 7	14	21
1981		$Y = 2.72\ x^{0.62}$	$Y = 10.6\ x^{0.38}$	$Y = 19.3\ x^{0.29}$
	r	0.69	0.62	0.73
	N	19	18	15
	T	3.93	3.16	3.85
1980		$Y = 21.8\ x^{0.29}$	$Y = 6.8\ x^{0.59}$	$Y = 19.8\ x^{0.35}$
	r	0.58	0.64	0.49
	N	16	18	18
	T	2.66	3.33	2.25
1979		$Y = 30.5\ x^{0.24}$	$Y = 76.5\ x^{0.03}$	$Y = 211.7\ x^{-0.28}$
	r	0.86	0.23	0.58
	N	8	8	10
	T	4.13	0.58	2.01

Table 17

BOD REDUCTION AS A FUNCTION OF INITIAL LOADING

(Y = BOD Reduction, %; x= Initial loading kg/ha)

Year	Retention time (days) 7	14	21
1979	$Y = 197\ x^{-0.17}$	$Y = 137\ x^{-0.08}$	$Y = 68\ x^{-0.06}$
	$r = 0.11$	$r = 0.38$	$r = 0.03$
	$N = 10$	$N = 10$	$N = 7$
1980	$Y = 86\ x^{-0.06}$	$Y = 40\ x^{0.12}$	$Y = 4.9\ x^{0.49}$
	$r = 0.11$	$r = 0.32$	$r = 0.91$
	$N = 15$	$N = 14$	$N = 14$
1981	$Y = 24\ x^{0.19}$	$Y = 22\ x^{0.22}$	$Y = 2.2\ x^{0.65}$
	$r = 0.55$	$r = 0.70$	$r = 0.64$
	$N = 10$	$N = 12$	$N = 9$

Table 18

CORRELATION BETWEEN PO_4 REDUCTION AND RETENTION TIME

$Y = 100\ (1-ae^{-bt})$ Y = % PO_4 reduction (mean values for each year)

t= retention time, days (t = 7, 14, 21 used in regression)

a, b = regression constants

Location	a	b	r	N	T
LINED LAGOON	0.62	0.031	0.78	9	3.3
UNLINED LAGOON	0.92	0.065	0.66	9	2.3
DITCH 1	0.61	0.066	0.54	9	1.7
DITCH 2, 3	0.56	0.064	0.55	18	2.6

Table 19

CORRELATION BETWEEN BOD REMOVAL AND RETENTION TIME

$Y = 100\ (1 - ae^{-bt})$

Y = BOD removal, % t = retention time, days a,b = regression constants (mean values of Y for t = 7, 14 and 21 days in 1979, 1980 and 1981 used in regression)

Location	a	b	r	N	T
LINED LAGOON	0.47	0.036	0.39	9	1.12
UNLINED LAGOON	0.62	0.090	0.70	6	1.96
DITCH 1	0.21	0.003	0.03	9	0.08
DITCH 2, 3	0.22	0.094	0.62	9	2.10

Table 20

RATE OF PHOSPHATE REMOVAL (kg/d) AS A FUNCTION OF INITIAL LOAD (kg) AT THE BEGINNING OF EACH PERIOD

$Y = ax^b$

Y = PO_4 removal, kg/d a, b = regression constants

x = PO_4 load, kg

	a	b	r	N	T
			1979		
LINED LAGOON	0.102	0.53	0.584	7	1.61
UNLINED LAGOON	0.041	1.32	0.974	7	9.61
DITCH 1	0.036	0.58	0.685	8	2.30
DITCH 2, 3	0.115	1.25	0.952	14	10.8
			1980		
LINED LAGOON	0.018	1.40	0.81	13	4.5
UNLINED LAGOON	0.012	1.56	0.73	16	3.9
DITCH 1	0.084	1.416	0.84	17	5.9
DITCH 2, 3	0.082	1.234	0.88	32	10.0
			1981		
LINED LAGOON	0.017	1.44	0.96	15	12.4
UNLINED LAGOON	0.015	1.36	0.68	18	3.7
DITCH 1	0.087	1.24	0.93	15	9.1
DITCH 2, 3	0.043	1.25	0.68	40	5.7

Table 21

RATE OF BOD REMOVAL (kg/day) AS A FUNCTION OF

INITIAL BOD LOAD (kg) AT THE BEGINNING OF EACH PERIOD

$Y = ax^b$

Y = BOD Removal, kg/d a, b = regression constants

x = BOD Load, kg

	a	b	r	N	T
			1979		
LINED LAGOON	0.05	1.21	0.83	14	5.1
UNLINED LAGOON	0.27	0.78	0.59	11	2.2
DITCH 1	0.11	1.10	0.82	7	3.2
DITCH 2, 3	0.08	1.52	0.93	14	8.6
			1980		
LINED LAGOON	0.070	0.90	0.78	15	4.5
UNLINED LAGOON	0.026	1.21	0.67	14	3.2
DITCH 1	0.065	1.17	0.93	13	8.4
DITCH 2, 3	0.079	1.15	0.91	28	11.3
			1981		
LINED LAGOON	0.038	1.22	0.88	11	5.6
UNLINED LAGOON	0.069	0.95	0.85	11	4.8
DITCH 1	0.071	1.23	0.98	11	14.8
DITCH 2, 3	0.067	1.17	0.91	21	9.6

Data from 48 individual treatment runs over the three year period have been used to show the generalized performance of the artificial wetlands in Table 17. Mean values for minimum and maximum removal of PO_4 and BOD achieved at the end of various retention times are tabulated in the table. Large variations in the initial loading produced a variable performance. The percentage reductions given in the table refer to mass flows in kg.

Another measure of nutrient removal by the wetlands refers to the gross nutrient removal per day per unit growing area. Table 18 shows these values expressed as grams per day per square meter for the three year period. Mean response over the three-year period is given in Table 19.

The values convert to removal rates of about 500 kg/ha for PO_4 and about 1,770 kg/ha for BOD based on a 180-day growing season.

Table 22

MEASURED PO_4 AND BOD REDUCTIONS FOR VARIOUS RETENTION TIMES

	PO_4 Reduction (%)		BOD Reduction (%)	
Approximate retention time (days)	Mean Minimum	Mean Maximum	Mean Maximum	Mean Minimum
7	36	75	60	86
14	48	82	66	90
21	61	92	58	92

Table 23

PO_4 AND BOD REMOVAL RATES

($g/d/m^2$)

	1979		1980		1981	
SITE	PO_4	BOD	PO_4	BOD	PO_4	BOD
LINED LAGOON	0.12	0.98	0.14	0.67	0.21	0.25
UNLINED LAGOON	0.10	0.67	0.11	0.30	0.13	0.19
DITCH 1	0.19	1.25	0.36	2.46	1.08	2.03
DITCH 2	0.17	1.01	0.19	1.27	0.49	0.82
DITCH 3	0.18	1.117	0.18	1.20	0.54	0.49

Table 24

MEAN REMOVAL RATES ($g/d/m^2$)

SITE	PO_4	BOD
LINED LAGOON	0.16	0.63
UNLINED LAGOON	0.11	0.39
DITCH 1	0.54	1.91
DITCH 2, 3	0.29	0.99

NITROGEN, pH AND TEMPERATURE VARIATIONS

The concentration of nitrogen in the sewage before treatment ranged between 10.4 and 44.0 mg/L and this was considered to be low (Table 15). During treatment, the nitrogen concentration was reduced by over 88% to as low as 2.1 mg/L. The treatment system, in fact, became nitrogen deficient during several runs. It appears, therefore, from what has been observed during the three-year operation, nitrogen would not present any removal problem in wetland treatment systems. The following table shows the initial and final nitrogen loadings and the percentage reduction achieved during each run.

The pH and water temperatures were also monitored during all treatment runs and the data analysis did not show any dependence of the rate of nutrient removal on either of these variables. The following tables show the mean values of pH and temperature measured from various sites.

Table 25

Reduction in Total Nitrogen Loading During Various Treatment Runs

	1979				1980				1981		
Site	Run	Initial (kg)	Final (kg)	Reduction (%)	Run	Initial (kg)	Final (kg)	Reduction (%)	Run	Initial (kg)	Final (kg)	Reduction (%)
LINED	1	23.9	1.3	90.4	1	52.24	11.52	77.9	1	38.0	3.4	91.0
	2	60.8	40.7	33.1	2	101.4	3.9	96.1	2	22.2	1.9	91.4
					3	26.0	3.3	87.2	3	20.8	2.6	87.5
UNLINED	1	24.4	3.5	85.6	1	27.7	2.5	90.9	1	36.9	2.3	93.8
	2	23.9	7.6	68.4	2	35.6	1.7	95.1	2	15.5	2.2	85.8
									3	19.6	1.7	91.3
DITCH 1	1	1.1	0.1	91.4	1	4.4	0.4	91.0	1	3.4	0.1	96.2
	2	2.6	0.2	92.1	2	5.0	0.2	95.7	2	2.4	0.3	90.7
					3	3.9	0.2	96.1	3	1.7	0.2	87.1
					4	1.7	0.4	76.9	4	1.7	0.4	78.3
									5	3.6	0.9	76.4
									6	4.2	0.1	97.9
DITCH 2	1	0.64	0.1	89.4	1	2.2	0.02	90.9	1	2.8	0.1	98.2
	2	2.4	0.2	90.3	2	2.5	0.3	88.7	2	1.5	0.1	92.7
					3	2.2	0.04	98.4	3	0.9	0.04	95.5
					4	1.3	0.2	83.9	4	3.1	0.5	83.9
DITCH 3	1	0.94	0.23	74.6	1	2.0	0.1	95.5	1	2.7	0.1	95.9
	2	2.9	0.2	92.2	2	2.5	0.1	96.0	2	1.1	0.7	66.7
					3	1.7	0.1	91.7	3	1.2	0.1	93.3
					4	1.1	0.2	84.2	4	2.5	0.3	88.8

Table 26
Measured pH Values During 1980

Date	L_L	U_L	D_1	D_2	D_3	Mean
22/05/80			7.5	7.5	7.5	7.5
26/05/80	7.7	7.7	8.1	8.3	8.2	8.0
29/05/80	8.3	8.1	8.1	8.3	8.1	8.2
2/06/80	8.6	8.1	8.0	8.4	8.0	8.2
5/06/80	9.3	8.6	8.3	9.0	8.3	8.7
9/06/80	9.3	8.7	8.1	8.8	8.6	8.7
12/06/80	9.1	9.2	8.4	8.8	9.0	8.9
16/06/80	9.0	9.0	8.1	8.5	8.7	8.7
19/06/80	8.5	8.8	8.9	8.6	8.5	8.7
23/06/80	8.7	8.9	8.2	8.3	8.5	8.5
26/06/80	9.0	8.6	8.2	8.3	8.3	8.5
30/06/80	9.4	8.6	8.8	8.9	8.6	8.9
3/07/80	9.7	8.5	8.5	9.2	8.6	8.9
7/07/80	9.9	8.6	8.1	8.4	8.2	8.6
10/07/80	7.9		8.0	8.1	8.0	8.0
14/07/80	8.9	8.2	8.0	8.1	7.9	8.2
17/07/80	9.9	9.5	8.2	8.2	8.1	8.8
21/07/80	10.1	8.0	8.2	8.1	8.4	8.6
24/07/80	10.4	8.3	8.2	8.0	8.0	8.6
28/07/80	10.0	8.9	8.1	8.1	8.2	8.7
31/07/80	9.7	9.1	8.4	8.0	8.2	8.7
4/08/80	9.4	9.0	7.7	8.1	7.9	8.4
7/08/80	9.9	9.2	8.0	8.1	8.1	8.7
11/08/80	9.9	9.5	8.0	7.6	8.0	8.6
14/08/80	9.8	9.1	7.9	7.9	8.0	8.5
18/08/80	9.5	8.5	7.9	8.0	8.1	8.4
21/08/80	9.1	8.5	7.9	7.9	8.1	8.3
25/08/80	8.4	8.0	7.6	7.9	8.3	8.0
28/08/80	8.2	7.8	7.8	7.9	7.8	7.9
2/09/80	8.6	8.0	7.7	7.7	8.4	8.1
4/09/80	8.3	8.1	7.8	7.8	8.6	8.1
8/09/80	8.3	8.2	7.7	7.9	8.4	8.1
11/09/80	8.4	8.4	8.1	7.9	8.3	8.2
15/09/80	8.2	8.3	8.1	8.1	8.1	8.2
18/09/80	8.3	8.3	8.1	8.1	8.1	8.2
22/09/80	8.3	7.9	7.9	8.1	7.9	8.0
29/09/80	8.7	8.7	8.4	8.4	8.6	8.6
2/10/80	8.1	7.9	7.7	8.2	8.1	8.0
6/10/80	8.2	7.8	7.9	8.0	8.4	8.1
9/10/80	8.1	8.3	7.8	7.8	7.9	8.0
14/10/80	8.4	8.6	7.9	8.2	8.2	8.3
16/10/80	8.1	8.4	7.7	7.8	7.8	8.0
20/10/80	8.3	8.6	7.9	8.1	8.1	8.2
23/10/80	8.0	8.5	7.8	7.9	8.1	8.1
27/10/80	8.3	8.6	7.9	8.0	8.1	8.2
30/10/80	8.4	8.6	8.0	7.9	8.4	8.3
3/11/80	8.2	8.6	7.8	7.8	7.9	8.1
Mean	8.8	8.5	8.0	8.1	8.2	8.3

Table 27
Measured pH Values During 1981

Date	L_L	U_L	D_1	D_2	D_3	Mean
20/05/81	8.0	8.1	8.1	8.1	8.1	8.1
26/05/81	8.9	8.6	8.7	9.3	8.5	8.8
2/06/81	9.1	9.1	8.1	8.6	8.5	8.7
9/06/81	8.8	9.3	7.9	8.0	8.5	8.5
15/06/81	8.8	9.4	7.9	8.6	8.5	8.6
23/06/81		9.5	7.6	8.0	9.0	8.5
29/06/81		9.5	7.7	8.0	8.7	8.5
6/07/81		9.3	8.1	7.9	8.7	8.5
14/07/81	9.0	9.0	8.4	8.7	8.2	8.7
21/07/81	9.0	8.5	7.7	7.9	7.9	8.2
27/07/81	8.7	9.3	8.1	8.3	8.1	8.5
4/08/81	8.6	8.3	8.0	8.3	8.1	8.2
11/08/81	8.9	8.6	8.0	8.7	8.2	8.5
14/07/81	7.9	7.8	7.8	8.0	7.9	7.9
18/08/81	8.0	8.2	7.6	7.9	7.8	7.9
25/08/81	8.5	8.6	7.8	8.5	8.0	8.3
1/09/81	8.2	8.2	7.8	8.4	8.1	8.1
8/09/81	8.3	7.9	8.0	8.5	8.2	8.2
15/09/81	8.2	8.3	7.6	7.6	8.1	8.0
22/09/81	8.2	8.6	8.0	7.8	7.8	8.1
29/09/81	8.3	8.7	7.9	8.0	8.0	8.2
7/10/81	8.4	8.9	7.9	7.8	8.0	8.2
13/10/81	8.3	8.7	7.7	8.0	8.0	8.2
20/10/81	8.5	9.4	7.7	8.7	8.1	8.5
27/10/81	8.3	9.1	7.5	7.7	7.7	8.1
4/11/81	8.4	9.0	7.8	8.0	7.8	8.2
10/11/81	8.4	8.9	7.3	8.0	7.5	8.0
17/11/81	8.4	9.2	7.9	8.0	8.0	8.3
24/11/81	8.4	8.8	7.3	7.6	7.3	7.9
Mean	8.5	8.8	7.9	8.2	8.1	8.3

Table 28
Mean Monthly Water Temperatures (°C)

Date	L_L	U_L	D_1	D_2	D_3
Sept./79	14.6	14.0	14.9	14.6	14.2
Oct./79	7.5	7.3	7.7	7.7	7.6
June/80	20.3	20.4	19.9	21.2	20.2
July/80	20.2	20.0	17.8	19.2	19.6
Aug./80	16.9	16.2	13.9	14.9	13.6
Sept./80	11.1	9.5	9.2	9.2	9.3
Oct./80	5.0	4.4	4.3	4.4	4.6
June/81	20.5	19.1	15.9	17.1	16.1
July/81	23.1	21.4	18.5	19.1	20.4
Aug./81	22.2	21.8	17.7	19.0	19.9
Sept./81	13.2	12.0	10.0	10.3	9.8
Oct./81	3.3	2.8	2.8	2.9	2.8
Nov./81	2.0	1.9	1.9	2.0	2.1

BACTERIOLOGICAL ANALYSIS

Guidelines established by Environment Saskatchewan (1975) require that coliform bacteria may not exceed 25×10^6 per 100 mL and 20,000 - 200,000 per 100 mL in effluents after undergoing primary and secondary treatment, respectively. In addition, the surface water quality objectives permit a coliform density of up to 5,000 per 100 mL and a faecal coliform density of up to 1,000 per 100 mL in waters to be withdrawn for treatment and distribution as a potable supply. In waters used for direct contact recreation and vegetable crop irrigation the limits for coliform and faecal coliforms are 1,000 per 100 mL and 200 per 100 mL, respectively.

Samples from the lagoons and ditches were obtained periodically during 1980 and 1981 and analysed for total coliforms and faecal coliforms using the Most Probable Number (MPN) technique. The results show that in almost all cases the coliform counts were below the provincial guidelines for effluents after secondary treatment. About 61% of measured coliform counts conformed to the objectives for potable supply of water after treatment (less than 5,000 per 100 mL) and about 42% conformed to the objective for contact recreation waters, i.e., less than 1,000 per 100 mL. In the case of faecal coliforms, about 87% of measured values were less than 1,000 per 100 mL and about 73% were less than 200 per 100 mL. The following tables summarize the results. The detailed measurements are given in the Appendix.

Table 29

Compliance of Treated Water In the Artificial Wetland

With Various Standards, Given as Percentage of

Measured Values Less Than the Standards

Type of Effluent or Use	Total Coliforms		Faccal Coliforms	
	Standard	Compliance	Standard	Compliance
	(counts/100 mL)		(counts/100 mL)	
After Primary Treatment	25×10^6	100%	-	-
After Secondary Treatment	$2x10^4$-$2x10^5$	97%	-	-
Potable Supply After Treatment Treatment	5×10^3	61%	1×10^3	87%
Water for Contract Recreation	1×10^3	42%	2×10^2	73%

Table 30

Summary of Bacterial Measurements

Location	Mean Counts	
	Total Coliforms (V.U./100 mL)	Faecal Coliforms (V.U./100 mL)*
	1980	
Lined	6.83×10^3	809
Unlined	1.16×10^3	67
D_1	993	200
D_2	400	122
D_3	1.0×10^3	125
	1981	
Lined	3.86×10^4	5.53×10^4
Unlined	1.29×10^4	67
D_1	2.24×10^4	714
D_2	1.37×10^4	1.38×10^3
D_3	1.32×10^4	5.33×10^3

*Viable Units per 100 mL of sample.

PLANT DENSITY AND NUTRIENT REMOVAL

Almost all of the nutrients consumed by the plants such as cattail and bulrush are taken up through their root-rhizome system. As shown earlier the rate of uptake was influenced predominantly by the initial nutrient loading and the retention time. These operational parameters can be managed to maximize the nutrient removal from the treatment site. Also, site specific parameters such as the plant density, liner and gravel substrate can be appropriately incorporated to improve nutrient removal. The plant density increases during successive years as has been the case at Humboldt.

No measurement of plant density was made in 1979 and the measurements obtained in 1980 and 1981 are given in Table 2. Plant density, representing both cattail and bulrush in the wetlands, increased drastically in the lined lagoon and less significantly in other sites. The rate of PO_4 removal expressed as grams per day per square metre was highly correlated with the plant density in the following form:

$$Y = (0.09)\ e^{(0.0113)\rho}$$

where Y is the rate of PO_4 removal per unit area, $g/d/m^2$ and ρ is the plant density, stems/m^2.

With a correlation coefficient of 0.898 the regression is significant at 0.1% level. On the other hand, the correlation between the rate of BOD uptake and the plant density broke up into two distinct relationships separately for 1980 and 1981. Both were linear with high correlations significant at 0.1% level. The following are the regression equations obtained.

1980

$Y = 0.134 + (0.015)\rho$

$r = 0.956$; $N = 5$; $t = 5.6$

1981

$Y = -0.713 + (0.012)\rho$

$r = 0.984$; $N = 5$; $t = 9.6$

Where Y is the rate of BOD removal per unit area, $g/d/m^2$ and ρ is the plant density, stems/m^2.

These are shown in Figures 2 and 3.

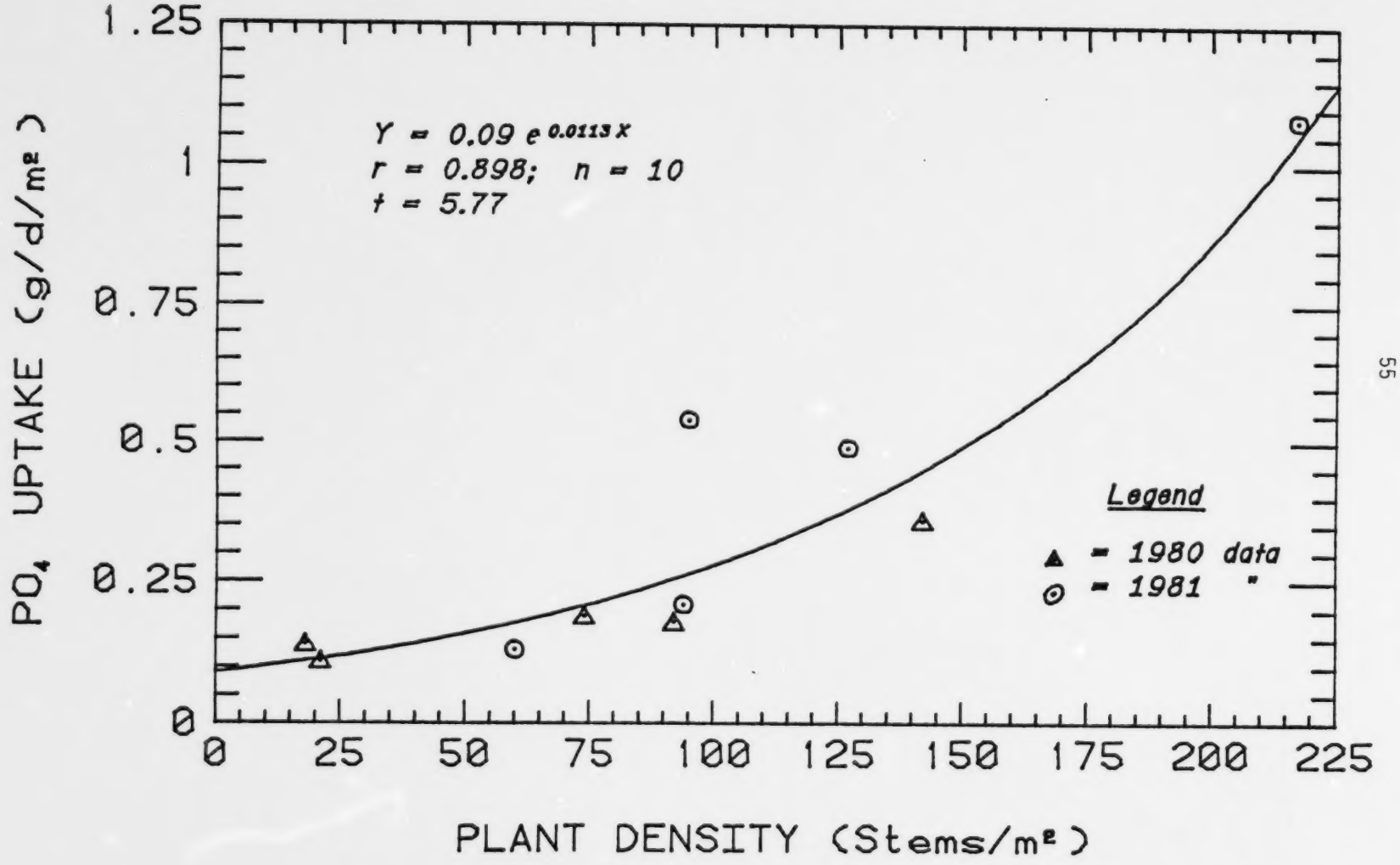

Figure 2 PO_4 Uptake as a Function of Plant Density

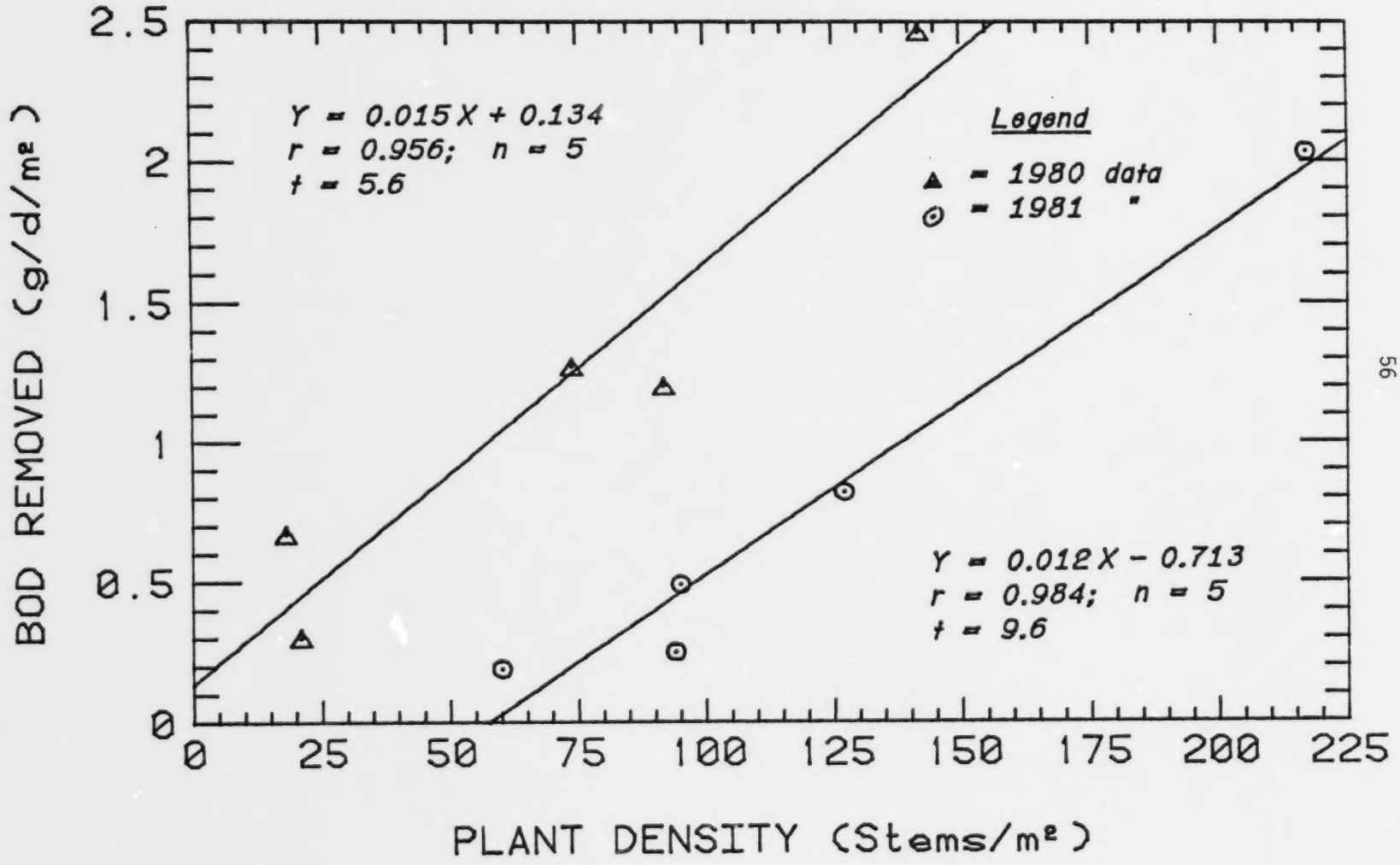

Figure 3 BOD Uptake as a Function of Plant Density

HARVESTING

Plants from the demonstration site were harvested manually, usually at the end of the growing season. However, in 1980 and 1981 a few random harvestings were done to collect samples for a different study on the feed value of the harvested plants.

Manual harvesting did not prove to be either inefficient or unduly labour intensive. Until mechanical harvesters which can be adapted to lagoons are made available, using a sickle mower to cut plants above ice, after freeze-up may prove to be helpful.

Harvesting the above-ground biomass at least once should be scheduled so that the nutrients would not leach back into the waters from dead leaves, and a part of the absorbed nutrients would be exported out of the wetlands. The cost of harvesting and collecting the plants should be included in the cost of operating the wetland system.

CONSTRUCTION PARAMETERS

In a given wetland the initial loading rate, retention time and the plant density are the most important variables which affect the nutrient removal process. However, the effect of these variables can be significantly modified by parameters related to the construction of these wetlands. The economics of wastewater treatments is also greatly affected by the construction costs which include the cost of excavating, lining the sites and supplying the gravel. It is, therefore, important to determine if using a lagoon instead of a ditch will significanctly affect the efficiency of nutrient removal. Area of the lagoon or the length of the ditch required to provide treatment can be optimized for a given volume of the effluent by using the minimum retention time and reasonable estimates of nutrient removal. At the same time it is essential to understand the advantages of incorporating special construction features such as liner, and the gravel substrate in relation to their costs.

To evaluate the relative effects of these construction parameters, the percentage removal of PO_4 per plant density has been computed for various retention times. As the plant densities were not measured in 1979 the tables consist of data for 1980 and 1981 only. The parameter for comparison K^1 is given by

$$K' = \frac{(\Delta Q)\ 100}{Q_1 \rho}$$

Where ΔQ is the quantity of PO_4 removed during a given period in kg, Q_1 is the initial PO_4 loading in kg and ρ is the plant density in stems/m^2. Mean values of K' are indicated by $\overline{K'}$.

The data for comparing the various construction parameters for their effect on BOD removal were not consistent particularly in 1981. Most of the data for the ditches were not reliable due to the low initial BOD levels and subsequent rapid reduction to less than 30 mg/L. However, the data from 1980 and 1981 for the lagoons and the data from 1980 for the ditches have been analysed to provide the following tables.

LINER

The use of a liner isolates the underlying soil substrate from the plants and the effluent. This may be necessary in areas with highly permeable soils posing a danger of contaminating the groundwater. Bentonite clay, if available, can be used instead of a synthetic liner to reduce costs. The following table (Table 20) compares the lagoons with and without the liner for their nutrient removal efficiency.

Table 31

EFFECT OF LINER ON THE EFFICIENCY OF PO_4 REMOVAL

Retention time (days)	1980			1981			Mean $\left(\frac{\overline{K'}_{LL}}{\overline{K'}_{UL}}\right)$ for 1980 and 1981
	$\overline{K'}_{LL}$	$\overline{K'}_{UL}$	$\frac{\overline{K'}_{LL}}{\overline{K'}_{UL}}$	$\overline{K'}_{LL}$	$\overline{K'}_{UL}$	$\frac{\overline{K'}_{LL}}{\overline{K'}_{UL}}$	
Less than 9	3.0	2.1	1.4	0.8	0.4	2.0	1.7
11 - 16	2.8	3.0	0.9	0.8	0.6	1.3	1.1
17 - 23	3.1	3.6	0.9	0.9	1.0	0.9	0.9
30 - 35	3.6	3.6	1.0	0.9	1.25	0.7	0.9

Initially for short retention times the existance of the liner provided better performance than the lagoon without a liner. The soil mixed gravel substrate in the unlined lagoon acted as a buffer and it took longer for the roots to get exposed to the nutrient influx and consequently the system was slower to homogenize. However, for longer periods the unlined lagoon performed equally well or better than the lined lagoon. From an economic and construction points of view the advantage of using a liner during the short retention time does not appear to be attractive if the system is designed to operate with retention periods longer than two weeks.

Table 32

EFFECT OF LINER ON THE EFFICIENCY OF BOD REMOVAL

Retention time (days)	1980 $\frac{\overline{K'}_{LL}}{\overline{K'}_{UL}}$	1981 $\frac{\overline{K'}_{LL}}{\overline{K'}_{UL}}$	Mean $\left(\frac{\overline{K'}_{LL}}{\overline{K'}_{UL}}\right)$ for 1980 and 1981
Less than 7	0.9	1.5	1.2
8 - 14	1.3	2.3	1.8
15 - 21	1.3	0.9	1.1
22 - 28	1.2	0.9	1.1

The lined lagoon showed a greater efficiency in removing BOD than in removing PO_4, and the high rates of removal were maintained for retention periods of up to 21 days.

GRAVEL SUBSTRATE

Gravel substrates provide a highly permeable layer which readily exposes the root zone to the changes in the nutrient flux. They also provide large surfaces for microbial and algal growth which metabolise the nutrients in the influent. But if gravel sources are not easily accessible the cost of supplying gravel can be high. Table 22 compares the PO_4 removal efficiencies in ditch 1 with soil bottom and the ditches 2 and 3 with gravel bottoms. The mean of $\overline{K^T}$ values for ditch 2 and ditch 3 is denoted by $\overline{K^T}_{2,3}$. The $\overline{K^T}$ factor for the soil substrate changed very little when the retention time was increased. The advantage in using gravel substrates is clear from the table.

Table 33

EFFECT OF GRAVEL SUBSTRATE ON THE EFFICIENCY OF PO_4 REMOVAL

Retention time (days)	1980 $\overline{K'_1}$	1980 $\overline{K'_{2,3}}$	1980 $\frac{\overline{K'_{2,3}}}{\overline{K'_1}}$	1981 $\overline{K'_1}$	1981 $\overline{K'_{2,3}}$	1981 $\frac{\overline{K'_{2,3}}}{\overline{K'_1}}$	Mean for 1980 and 1981
less than 8	0.5	0.9	1.8	0.4	0.4	1.0	1.4
8 - 15	0.5	0.9	1.8	0.4	0.5	1.3	1.6
18 - 22	0.6	1.1	1.8	0.4	0.6	1.5	1.7
25 - 28	0.6	1.1	1.8	0.4	0.7	1.8	1.8
32 - 35	-	-	-	0.4	0.8	2.0	-

Table 34

EFFECT OF GRAVEL SUBSTRATE ON THE BOD REMOVAL

Retention time (days)	1980 $\overline{K'_{2,3}}$	1980 $\overline{K'_1}$	$\left(\frac{\overline{K'_{2,3}}}{\overline{K'_1}}\right)$
less than 7	1.0	0.6	1.7
8 - 14	0.8	0.6	1.3
15 - 21	0.9	0.6	1.5
22 - 28	1.0	0.6	1.7

The PO_4 removal was increased by 40 to 80 percent with the gravel substrate. Growing plants in gravel has definite advantage over the soil substrate for all retention times.

Ditches 2 and 3 with gravel substrates were more effective, up to 70 percent more, than the ditch 1 with soil bottom in removing BOD for short and long retention periods.

CONSTRUCTION METHOD

The configuration of the treatment site, in terms of shape and size, has both operational and construction implications. Table 24 compares the ditches 2 and 3 with the unlined lagoon, with respect to PO_4 removal.

Table 35

COMPARISON OF LAGOON AND DITCH OPERATIONS FOR PO_4 REMOVAL

Retention time (days)	1980			1981			Mean for 1980 and 1981
	$\overline{K'_{UL}}$	$\overline{K'_{2,3}}$	$\frac{\overline{K'_{UL}}}{\overline{K'_{2,3}}}$	$\overline{K'_{UL}}$	$\overline{K'_{2,3}}$	$\frac{\overline{K'_{UL}}}{\overline{K'_{2,3}}}$	
less than 9	2.1	0.9	2.3	0.4	0.4	1.0	1.7
11 - 16	3.0	0.9	3.3	0.6	0.5	1.2	2.3
17 - 23	3.6	1.1	3.3	1.0	0.6	1.7	2.5
25 - 28	-	1.1	-	0.9	0.7	1.3	-
32 - 35	3.6	-	-	1.3	0.8	1.6	-

The lagoon was far more efficient than the ditches in removing phosphorus. The PO_4 removal in the lagoon was up to 2.5 times the removal in the ditches. Although it is more expensive to construct a lagoon than a ditch, operationally in terms of volume handling and material removal it is advantageous to set up a lagoon operation.

Table 25 compares the effectiveness of the unlined lagoon and ditches 2 and 3 in removing BOD.

Table 36

COMPARISON OF LAGOON AND DITCH OPERATIONS FOR BOD REMOVAL

Retention time (days)	1980		
	$\overline{K'}_{UL}$	$\overline{K'}_{2,3}$	$\frac{\overline{K'}_{UL}}{\overline{K'}_{2,3}}$
less than 7	2.7	1.0	2.7
8 - 14	2.5	0.8	3.1
15 - 21	2.7	0.9	3.0
22 - 28	3.5	1.0	3.5

The unlined lagoon removed BOD much more effectively than the ditches 2 and 3 by a factor of up to 3.5.

PUBLICATIONS

PUBLICATIONS ORIGINATING FROM THE WORK CONDUCTED AT SRC ON UTILIZING AQUATIC PLANTS FOR WASTEWATER TREATMENT

1. Lakshman, G. 1979. An Ecosystem Approach to the Treatment of Wastewaters, J. Environ. Qual., Vol. 8, No. 3
2. Lakshman, G., 1980. Aquatic Plants in the Treatment of Wastewaters, Changes in the Feed Value of harvested Plants When Grown in Nutrient-Rich Environment, SRC Internal Document
3. Lakshman, G., 1980. A Demonstration Project at Humboldt to Provide Tertiary Treatment to the Municipal Effluent Using Aquatic Plants, SRC Publication No. E-820-8-1-E-80
4. Lakshman, G., 1981. A Demonstration Project at Humboldt to Provide Tertiary Treatment to the Municipal Effluent Using Aquatic Plants, Progress Report No. 2, SRC Publication No. E-820-4-E-81
5. Lakshman, G., 1982. A Demonstration Project at Humboldt to Provide Tertiary Treatment to the Municipal Effluent Using Aquatic Plants, Progress Highlights, SRC Publication No. E-820-5-E-82
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7. Lakshman, G., 1982. The Physiological Influence of Growth Rate and Photosyntesis on the Nutrient Uptake in Cattail and Bubrush. (Paper under completion)
8. Lakshman, G. 1982. Optimizing Wetland Treatment of Wastewaters. (Paper under completion)
9. Lakshman, G., 1982. A Study to Evaluate the Potential of Cattail as an Energy Crop. SRC Publication No. E-820-6-F-82

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Saskatchewan Research Council
30 Campus Drive
Saskatoon, Saskatchewan
Canada
S7N 0X1